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Romantic Transfer from Thermodynamic Theories to Personal Theories of Social Control: A Randomised Controlled Experiment

Chen Chen [1,2,*], Si Chen [3], Helen Haste [4], Robert L. Selman [5] and Matthew H. Schneps [6]

[1] Faculty of Education, The University of Hong Kong, Hong Kong
[2] Science Education Department, Harvard Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[3] Department of Educational Psychology, The Chinese University of Hong Kong, Hong Kong
[4] Department of Psychology, University of Bath, Bath BA2 7AY, UK
[5] Harvard Graduate School of Education, Cambridge, MA 02138, USA
[6] Department of Computer Science, University of Massachusetts Boston, Boston, MA 02125, USA
* Correspondence: logancc@hku.hk or chen.chen@cfa.harvard.edu

Abstract: The transfer of learning is arguably the most enduring goal of education. The history of science reveals that although numerous theories have been transferred from the natural sciences to the socio-political realm, educational practitioners have often deemed such transfers romantic and rhetorical. We conducted an experiment that randomly assigned a sample of 292 college freshmen in China to two groups to learn different thermodynamic theories: entropy or self-organization theory. We examined whether the two groups may arrive at different implications about social (and government) control without explicit instructions. We found that participants who learned the theory of entropy were more likely to believe the social system would become chaotic over time without external control; thus, they preferred tightened social control. Whereas participants who learned self-organisation theory were more likely to believe that order may form from within a social system; therefore, they downplay external control and prefer stronger individual agency. Follow-up interviews showed that the participants' narratives about social control were largely consistent with the thermodynamic concepts they had learned. Our findings have critical implications for the recent trend in STEM education that promotes the teaching of cross-cutting concepts—seeking patterns from interdisciplinary ideas—that may implicitly prime students to borrow physical science theories to formulate personal social hypotheses and engage in moral–civic–political discourse.

Keywords: transfer of learning; science education; civic education

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1. Introduction

In an interview, the chemist Denham Harman recalled his conceptualisation and formulation of the free radical theory of ageing as follows [1]: 'I realized that free radicals [oxygen-containing molecules] could account for all the [erosive] phenomena that I knew about because they were irreversible reactions. At that time there was no datum to indicate they were going on in the human body, but it was quite obvious that they had to go on because it was just the nature of chemistry'. Following this reasoning, Harman theorized the free radical theory that deemed antioxidants such as vitamin C to be effective in preventing ageing, which was one of the most tenacious myths in the pharmaceutical industry [2]. This is an example of the 'romanticisation' of scientific theories—transplanting information from scientific models into one's personal life based simply on analogical resonance without direct empirical evidence. Harman is one of many scientists who have romanticised science in this way (for other examples, see [3]).

Many scholars in the field of science education have found parallel mapping between the psychology of learners and the reasoning of scientists in history (e.g., conceptual change

vs. paradigm shift) [4,5], known as the 'learner-as-scientist' model [6]. Feinstein [7] noted that citizens bring science to civic discourse 'in unpredictable ways that are shaped by personal motivations and cultural context'. Thus, it is important to assess science learners' tendency to freely transfer scientific concepts to civic discourse in ways that are similar to what scientists do but are unexpected to science teachers.

In this study, using a randomized experiment and a mixed-methods approach based on quantitative and qualitative data, we examined whether a sample of college students from China could spontaneously transfer entropy theory (the second law of thermodynamics) or self-organisation theory to their personal (political) theories and narratives about social entropy or social control.

This study is important in that the romantic transfer from scientific models may appear more convincing and powerful than textbook knowledge because it is intuitive and generated by the learners themselves. However, such intuitions are not always socially or politically neutral ideas. Darwin and Huxley [8] worried about transferring evolution theory to human society. Similarly, considering society as a thermodynamic system has implicit, yet strong, implications for governance and democracy. Kenneth Bailey [9], a mathematician and sociologist, first introduced the term "social entropy" as being analogical to the thermodynamic theory of entropy as a sociological theory. In one frequently cited example, the American physicist Alan Lightman [10] instructed his students to reason about the collapse of the Soviet Union using the second law of thermodynamics. However, there has yet to be a study (in any culture, to the best knowledge of the authors) to investigate to what extent this transferential inspiration spontaneously occurs in novice science learners. Science educators seldom consider themselves responsible for students' anecdotal civic beliefs, especially if the civic ideas are not part of the course content. Nevertheless, if evidence shows students may self-generate social–political ideas metaphorically from science lessons, science educators should reconsider and reposition their roles in civic education.

2. Definition

The romantic transfer of science is an informal metaphor-making process that carries over accepted knowledge from the scientific realm to justify, infer, and generate new understanding in social or other non-scientific domains. It borrows the intricacy, universality, and profundity of the scientific establishment to inspire life wisdom; however, it does not follow a rigorous scientific process to falsify personal theories. Multiple studies have explored the phenomenon of 'coexistence' among science learners—their ability to hold self-developed imprecise intuitions and, at the same time, precise understanding of scientific concepts, whereas the two can be selectively activated depending on the context [11–14].

3. Literature

3.1. Romantic Transfer in Education

Education researchers have increasingly called for a 'broader scope' [15] of curriculum design in science education to bring about a 'philosophical turn' [16] and a 'cultural border crossing' [17] that can deliver 'companion meaning' [18] in 'beliefs and values' [19] to promote liberal ideas and a democratic society [20].

Hadzigeorgiou [21] intended this romantic approach to promote (a) emotional sensitivity to nature; (b) acuity to one's own senses and experiences; (c) holistic experiences; (d) an appreciation of mystery and wonder, (e) a transformation of worldviews; and (f) a philosophical understanding of science [22,23].

3.2. Transfer of Learning

Transfer of learning, by definition, is that learners use what they learned in one context (time, space, or knowledge domain) in another context (e.g., [24]). A substantial amount of research has concluded that transfer does occur [25,26]. For example, Ball [27] showed that students were able to transfer their knowledge of the diffusion-limited aggregation principle (a process by which particles undergo a random walk to form tree-like aggregate

structures), which they had learned from lectures on copper sulphate, to inform their understanding of the formation of civilization.

However, many other studies have argued that transfer rarely occurs, particularly to the target domain that educators most wish to affect [28]. Multiple recent review articles about the transfer of learning [24,29] have concluded that transfer is both ubiquitous and rare. Partly due to the lack of direct evidence of the transfer of learning, researchers have recently begun to revisit and expand the definition of transfer (e.g., [30]). Lobato [31,32] called for a shift from observing how learners apply knowledge to improve their performance in the target domain designated by experts (the traditional view) to observing how learners either notice (or recognise) similarities or discern dissimilarities [33] between domains (the actor-oriented view). Forsyth [34] further proposed an expansion of the similarity metric to long-distance transfer, relaxing a strictly analogous form of structural mapping to a generic thematic similarity.

3.3. Unexpected Transfers

Once the transfer of learning is no longer restricted to the domains designated by teachers, there is increasing evidence that learners may freely transfer (or generalise) their science knowledge to unexpected domains [35–38]. Further complicating the transfer of learning, these open-ended, spontaneous metaphor-making processes—especially romantic ones—are not socially or politically neutral endeavours. For example, Brem et al. [39] reported concerned students worried that evolution might promote social Darwinism, racism, elitism, and selfish moral values.

In a series of randomised trial studies, Donovan [40,41] showed that a genetic biology curriculum that discussed the genetic basis of racial differences in skeletal structure (treatment group) made students more likely to provide genetic explanations for racial differences in achievement gaps [40], compared with a nearly identical curriculum that did not use genetic terminology (control group). Moreover, the students in the treatment group became 'less interested in socializing across racial lines and less supportive of policies that reduce racial inequality' [41]. Thus, romantic transfer from science, although sometimes poetic, may have unintended, controversial, or seriously negative social consequences.

4. Research Question

We investigated whether two scientific concepts—entropy theory and self-organisation theory—could cause novice learners to make different romantic transfers, in terms of action endorsement and narratives, around the same topic of social control. Entropy is a thermodynamic theory according to which an enclosed system unavoidably becomes chaotic unless order is restored using external energy (e.g., the diffusion of gas). According to self-organisation theory, some open environments can develop systematic patterns without external intervention (e.g., snowflakes). Both concepts come from the family of thermodynamics, but at the level of superficial denotation, they make different predictions about the order of a thermodynamic system. Although the theories are not inherently mutually exclusive, the students from each group were only introduced to one of them.

We explored potential romantic transfer in several case studies by asking whether the participants in the different groups expressed different expectations of social order and different preferences concerning social control. We hypothesized that the entropy group would give a stronger endorsement to interventionist social control compared to the self-organization group. In a follow-up in-depth interview with a subset of the sample, we explore to what extent the participants applied the thermodynamic theories to their narratives about social control.

5. Methods

5.1. Sample

We recruited 292 freshmen from a vocational college located in an agriculture-based third-tier city in southwestern China. Most of the students were vocational mechanical engineering majors (e.g., studying vehicle reparation), although some majored in non-

engineering subjects (e.g., finance). All of the participants were freshmen and had only been attending college for two months.

At this vocational college, all freshmen were required to enroll in ideology education lectures, which typically covered a wide range of topics, including mental health, ideology, national and international political news, and other subjects addressed by visiting scholars. The school routinely grouped students into classes of approximately 140 individuals each. Each class attended the ideology lectures at different times during the week. Students from two of the classes participated in the current study. The full sample was randomly assigned to two separate classrooms.

The students were told that they would hear a popular science lecture delivered in a story-telling style and that the course would teach them some interesting scientific theories. The students were told that they would be asked to give feedback on the lectures to help the curriculum designers evaluate and improve the course. The participants were also told that they would be asked to answer many unrelated questions to help the curriculum designers prepare lectures on other topics. The questionnaire asked for the students' IDs but not their names. All of their responses and personal information were kept confidential.

5.2. Procedure

Figure 1 summarises the experimental procedure. Using two lecture halls, we randomly assigned 140 subjects to one group that attended a lecture on entropy (the ENT group) and 152 to a group that attended a lecture on self-organisation (the SEO group). The two groups were well-balanced in terms of gender (ENT group: 33% male; SEO group: 37% male), age (ENT group mean = 19.08, SD = 0.81; SEO group mean = 18.99, SD = 0.79), and whether the students were STEM majors (ENT group 77%; SEO group 80%).

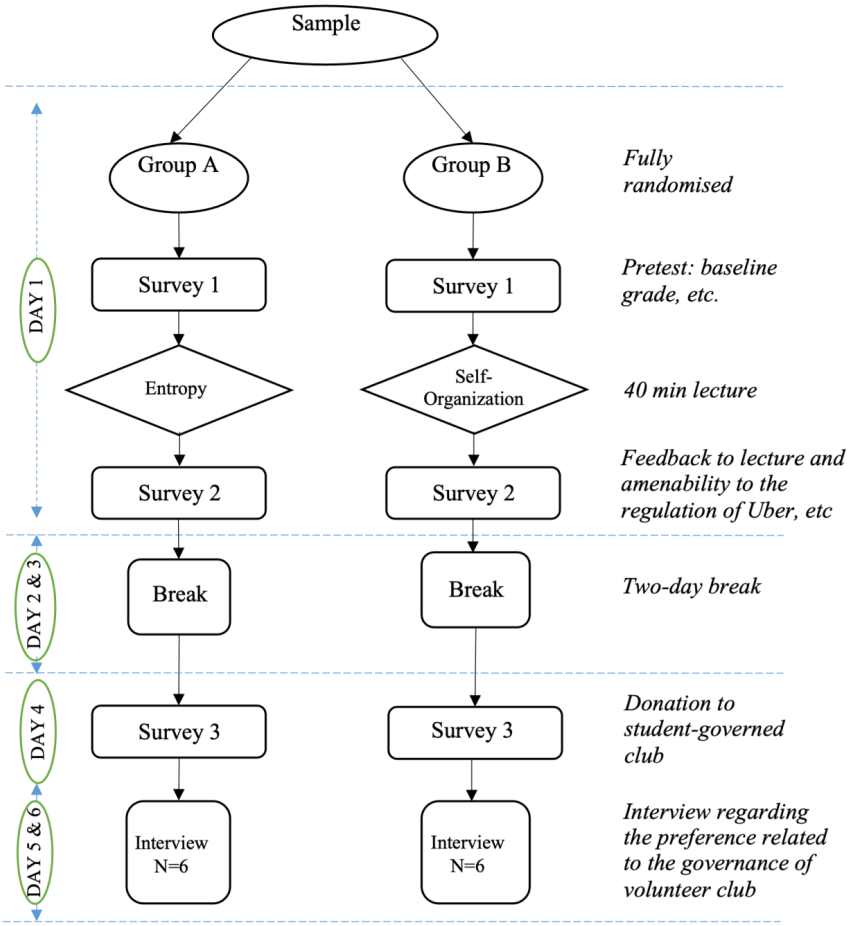

Figure 1. The procedure for the experiment. Before the participants attended the lectures, they completed Survey 1 (a pre-survey). After the lectures, they completed Survey 2 (the first post-survey).

Two days later, at the beginning of their ideology education courses, the participants completed Survey 3 (the second post-survey). When the students submitted their responses to Survey 1, they each indicated whether they would be willing to participate in a voluntary follow-up interview. During the lectures, the research assistant randomly selected six interviewees from the volunteers in each group. At the end of the lectures, before Survey 2 was administered, the selected interviewees were asked to provide their contact information. The interviewees were also notified that they could leave early and decline to participate in the post-surveys.

5.3. Material

5.3.1. Survey 1 (Pre-Survey)

Survey 1 contained the pre-survey items and collected the participants' background information, including their gender, age, and major. Survey 1 also asked the participants how much money (ranging from 0 to 50 RMB) they would be willing to donate per year to a charity of any kind (hereafter, budget).

5.3.2. Survey-2 (First Post-Survey)

The first part of the survey asked about the participants' general experience of the lecture. The second part of the survey contained four case studies that each included nine questions measured on a 4-point Likert scale. The four cases were as follows. The first case study asked whether head teachers should be assigned to MOOCs to help students organise the knowledge structure. The second case study asked whether the government should intervene in the Uber market. By 2015, when this study was carried out, Uber had entered the taxi market in several large Chinese cities. This new business model prompted a heated debate in the news media about its safety, legitimacy, and regulation. Because Uber had not yet entered the city where our experiment was conducted, it was a pressing social topic that was new to the participants. The third case study asked the participants to consider two hypothetical political parties, one promoting strong citizens over a weak government and the other promoting a strong government over citizens, and to indicate which one people should support. The fourth case study asked whether the government should intervene in the activities of small online businesses (e.g., the Chinese equivalent of eBay sellers). The wording of and rationale for each case study are shown in Supplementary File S1. These nine items probed different positions in different cases, and they were not designed to measure a single construct. Thus, the nine items were not combined into a composite score but were each to be treated as a separate outcome variable.

Case I concerned the organisation of knowledge and learning plans. Cases II and IV concerned government intervention in free markets. Case II was a new topic to the participants, and Case IV was a familiar topic. Case III concerned the power relationship between citizens and the government. All four cases were related to order and control, but they were specified in different domains to which the participants might make romantic transfers.

5.3.3. Survey-3 (Second Post-Survey)

In this survey, we only asked one question. At the research team's request, this question was embedded in a larger questionnaire sent out by the student union of the sample school. The student union was preparing to launch a student volunteer club, and the school administration had agreed to allow students to organise the club to the greatest extent possible. The original survey contained more items that asked about the students' attitudes towards and interest in participating in volunteer work. However, the research team only had access to the item that asked the participants how much money (no more than 50 Chinese yuan) they would be willing to donate to the proposed student-governed volunteer club (the baseline budget was accounted for in Survey 1).

5.4. Intervention

The ENT group received a 40 min lecture on entropy in thermodynamics. The key message was that entropy is a measure of disorder, and in an enclosed system, entropy will only increase unless external higher-ordered energy is channelled into the system. The lecturer's examples included video/animated clips of the dispersal of sand, liquid, and gas particles, restoring battery power from external electrical power, and an air conditioner using electrical power to cool a room. Midway through each clip, the lecturer asked the students to discuss the spontaneous change in the system over time and compare the entropy of the system in different states. The students discovered that in every example, entropy could only increase spontaneously. For each of the examples, the lecturer also asked the students to think of as many ways as possible to reduce the entropy in the system. For example, they could change the shape of a pile of sand using a bucket, cool the air using air conditioning, and filter ink. For each of their solutions, the students were asked to identify the source, flow, and final destination of the energy. The students realised that reducing entropy always involves additional or external energy.

The SEO group received a 40 min lecture on self-organisation theory in thermodynamics. The key message was that an open system can sometimes self-organise into regular and even intricate patterns through a bottom-up, locally interactive, and self-reinforcing feedback loop without an external design. Such systems tend to be highly efficient, adaptive, and robust, yet wholly decentralised. The lecture used snowflakes as the primary example, presenting different beautiful structures of snowflakes and playing a five-minute clip of how water molecules gradually organise themselves into delicate snowflakes based solely on local interactions. The lecturer also presented examples of local interactions in crowds of animals, such as flocks of birds and schools of fish, emphasising the fact that the head bird emerges from the crowd and other birds only follow and respond to adjacent birds. The lecture also introduced the function of enzymes in self-organising biochemical reactions and emphasised that enzymes can speed up, but not change, such processes. At the end of the lecture, the lecturer showed video clips of how engineers developed self-organising materials based on self-organisation theory.

In each of the sessions, the lecturer introduced the key concept at the beginning of the session and reiterated the key concept in every example. In each of the sessions, the lecturer mentioned that the target concept could be widely observed in the domains of physics, chemistry, and biology but did not mention its application in human society. For example, the lecturer avoided stating that 'a room can only become messier and messier unless someone cleans it' to explain entropy, although this is a common example in textbooks. To focus on conceptual understanding and to make the lectures beginner-friendly, there were no mathematical treatments of any of the theories.

Each class session was instructed by a physics teacher. The instructor and participants in each session were not aware of the content of the other session when the intervention took place.

5.5. Interviews

The interviewer guided the conversation with a sequence of overarching questions, as shown in Table 1.

Table 1. Interview guiding questions and their rationales. In the semi-structured interviews, the interviewer read the cases, such as the regulation of Uber or the governance of a volunteer club, to the interviewee. Afterward, the interviewer guided the conversation with a sequence of overarching questions. Unlike the survey questions, which asked the participants to rate opposing options, the interview questions required the participants to choose their preferences and provide justifications.

Question	Rationale
1. Between the government version of Uber and the original, private Uber, which do you prefer, and why? OR: Between student-governed clubs and school administrator-governed clubs, which do you prefer, and why?	In each of the cases presented, there are two options. One suggests a more centralised, hierarchical regulation that is consistent with the entropy framework; the other suggests a self-autonomous regulation that is consistent with self-organisation theory. These questions ask the participants to state their preference and their justifications.
2. According to this passage, some people believe that private Uber (or student-governed clubs) will necessarily become disordered. What is your view? 3. In your opinion, what is the source of disorder, and what is the key to increasing order in the Uber market (or student organisations)?	These questions focus on order and disorder, using Uber or the club as an anchor to encourage the participants to reveal their mental models about order versus disorder. These questions challenge the participants to think about the advantages of or need for central hierarchical control. The questions require students to explain and justify their preferences.
4. According to this passage, some people believe that the government should exercise control over Uber. What do you think about this belief? OR: Some people believe that the school administration should play a leadership role in managing the club. What is your opinion? 5. Who do you think has more responsibility for the healthy organisation of the Uber market (or the student-governed club)? Do you think that there should be a leader? Who should be the leader? Why should this person (or agency or group) be the leader? How is leadership formed?	These questions focus on key players and leadership.
6. This passage notes that some people believe that the government should leave Uber alone and not intervene. What do you think about this issue? OR: Some people would prefer the club to be governed by students autonomously. What would you prefer, and why?	These questions ask participants to reflect on the advantages of free markets or autonomous organisations. They require the participants to justify their preferences.
7. What will happen in the beginning and happen in the long term if there is very little government intervention in Uber? OR: What will happen in the beginning and in the long term if school administrators are not involved in the club?	These questions ask the participants to predict the trajectory of an unsupervised system.
8. So, you suggest . . . (quote the participant's summary of the statement). Under what conditions would you consider the opposite stance?	This question asks the participants about exceptions. It attempts to probe boundaries and conditions.

5.6. Analysis

For the case-study items, we conducted an ordered multinomial logistic regression analysis, treating the item responses as outcome variables and examining the main effect of the treatment while controlling for age, gender, and academic major. The second analysis considered the size of a donation to the student-governed club in the second post-test as the outcome variable. We used ordinary least squares regression to examine the main effect of the treatment while controlling for the baseline budget for charity. We also examined the interaction effect between the treatment and baseline budget. Although the participants came from different classes, we did not specify a hierarchical model because (1) we controlled for their academic major, which overlapped with their class nesting, and (2) the participants were completely randomly assigned to lectures at the individual level, not the class level.

6. Results

6.1. Ordered Categorical Items from the First Post-Test

Among the nine items in the first post-test, four showed statistically significant treatment effects (p-value < 0.05), while the other five did not reach significance. There was no interaction effect between the treatment and the other covariates. Figure 2 shows the mean log odd ratio (based on ordered multinomial logistic regression) and a 95% confidence interval between the ENT and SEO groups. In Figure 2, we converted the log odd ratios to odd ratios and reported the average group differences on a Likert scale. When the log odd ratio was greater than 0 (the line in the middle), the SEO group scored higher than the ENT group on average and vice versa. When both the lower and the higher bounds of the confidence interval were greater or smaller than 0, the difference between the two groups was statistically significant at the level of 0.05.

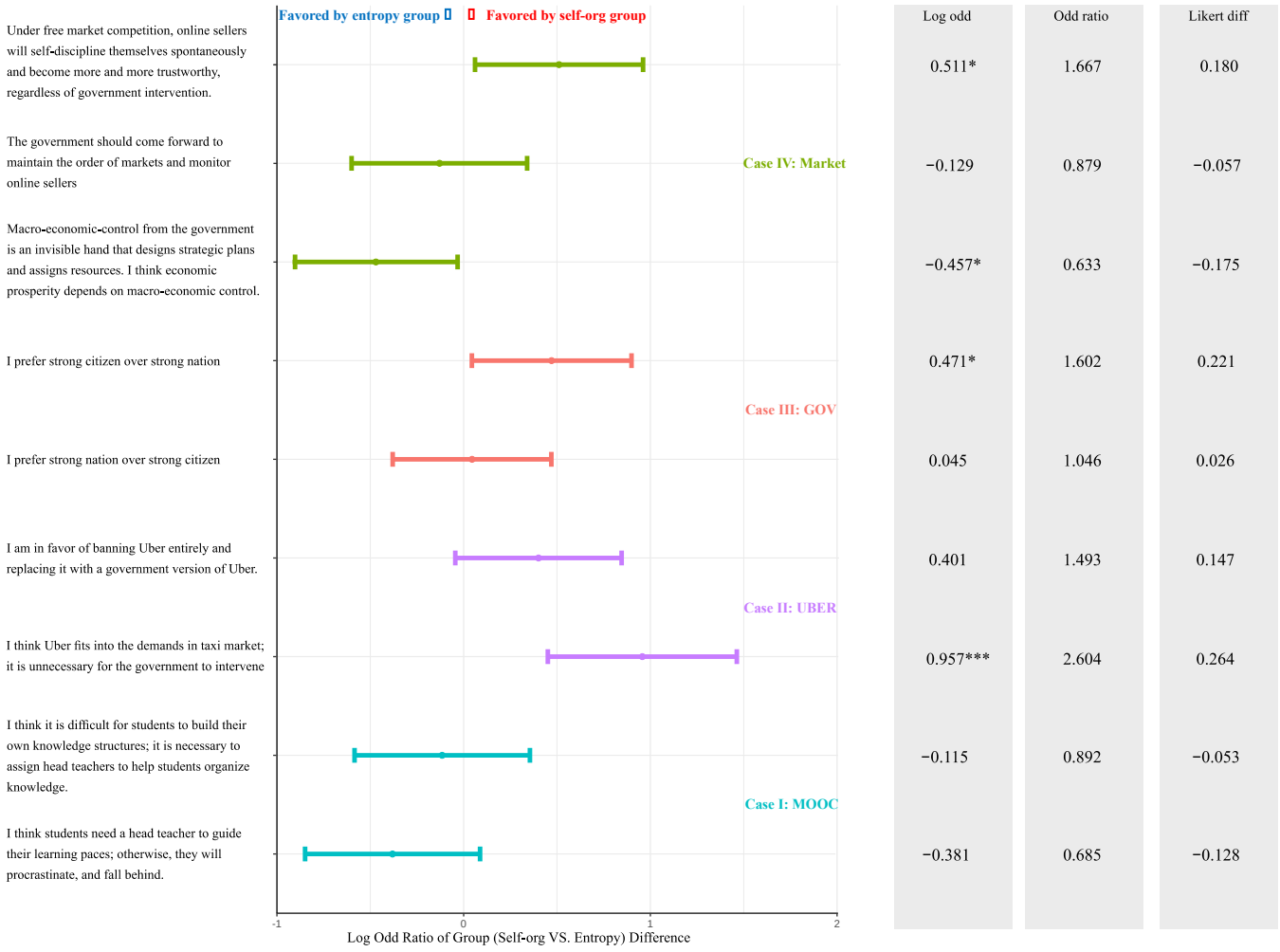

Figure 2. The mean log odd ratio between the self-organisation group and the entropy group on each of the post-test items. When the bar of an item is located on the left side of the dashed line, the entropy group has a higher score than the self-regulation group on that item. When the bar of an item is located on the right side of the dashed line, the self-organisation group has a higher score than the entropy group on that item. The colour of the bars denotes the topic of the case studies, as marked in the graph. *** $p < 0.001$, * $p < 0.05$.

We did not observe a treatment effect in the case of MOOCs. If we did not apply the Bonferroni p-value adjustment to penalise multiple comparisons (setting the p-value threshold at 0.05), we observed treatment effects in the cases of Uber, eBay sellers, and big vs. small government (four out of nine items). If we aimed to be conservative, applying

the Bonferroni p-value adjustment (setting the p-value threshold at 0.005), only one of nine items ('It is unnecessary for the government to intervene in Uber') had a significant treatment effect.

6.2. Donation

We detected a treatment effect on the amount the participants were willing to donate to the self-governed student club. The SEO group was willing to donate 3.00 RMB (se = 1.24, $p = 0.01$), which was more than the average willingness to donate from the ENT group. To put this in perspective, 3.00 RMB is equivalent to two cans of Coca-Cola or a half-order of fries at a Chinese McDonald's. Among the controlled variables, the baseline budget for charity was a significant predictor ($\beta = 0.45$, se = 0.04, $p < 0.001$).

Interestingly, there was an interaction effect between the treatment and baseline budgets for charity ($\beta = -0.18$, se = 0.09, $p = 0.04$). This indicated that the participants who had a low budget for charity were more sensitive to the treatment; indeed, at the lower end of the budget, the participants from the SEO group were willing to donate an average of 7.95 RMB (roughly 1 USD) more than the ENT group, whereas, at the upper end of the budget, it was impossible to distinguish between the two groups (post hoc test $F(1, 281) = 1.43$, $p = 0.23$). A post hoc test showed that the two groups were not statistically significantly different from each other when starting at budget = 25 ($F(1, 281) = 2.81$, $p = 0.09$). Figure 3 shows the interaction effect.

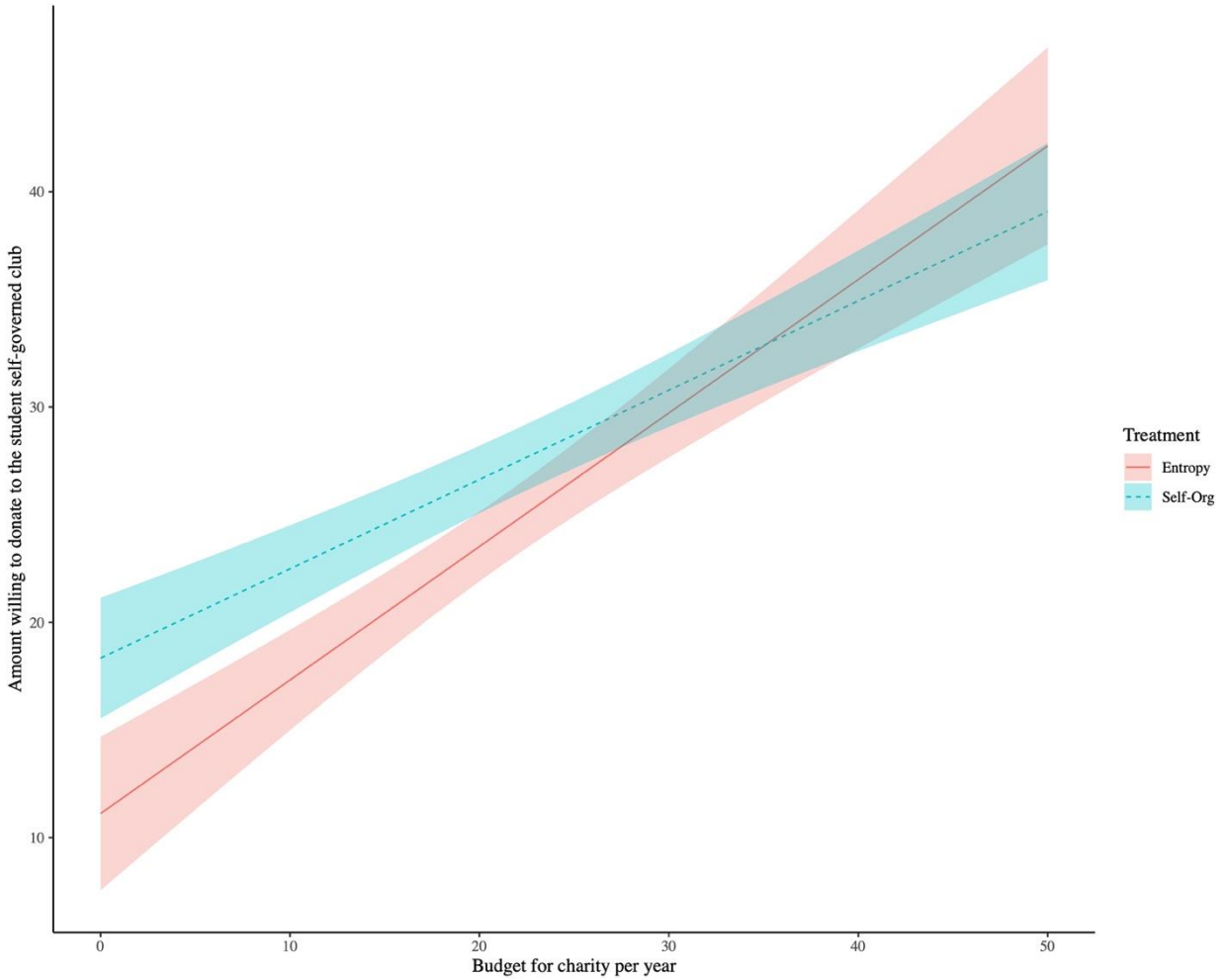

Figure 3. An interaction effect between treatment and baseline budget for charity. The participants who had a low charity budget were more sensitive to the treatment than the other participants, whereas, at the upper end of the budget, it was impossible to distinguish between the two groups.

6.3. Interview Themes

Five major themes emerged from the thematic analysis of the participants' reasoning about the two cases (Uber and the student club). As shown in Table 2, from the top to the bottom rows, they are (1) *Individual agency and attributes*, (2) *Unity, chaos, and spontaneity*, (3) *Leadership and its origin, eligibility, and function*, (4) *Natural changes over time*, and (5) *Responsibilities and functions of institutional structures*. The themes are briefly explained within Table 2 and detailed in Supplementary File S2 with examples. Each of the themes contained two positions (hands-on or hands-off). Two raters coded the transcripts separately, following the coding scheme for each theme and each position within the theme. In the first round of coding, the inter-rater reliability was 0.83. After discussing their disagreements, the two raters reached an inter-rater reliability of 0.92. The coding that was still subject to disagreement was not included in further analysis.

Table 2. Number of interviewees who made the specific positions under each theme, among the 6 interviewees from entropy and the 6 from self-organization group.

Themes	Positions Favoring the Hands-On Mindset		Positions Favoring the Hands-Off Mindset	
	Specific Positions	6 from ENT vs. 6 from SEO	Specific Positions	6 from ENT vs. 6 from SEO
Individual agency and attributes: individual members' behaviour in the system.	Some people intend to break the rules	6:3	People have good intentions	0:4
	Some members have poor skills and discipline	6:3	Some members have good skills and discipline	0:4
Unity, chaos, and spontaneity: how a group of people could either unite or fragment into chaos	Spontaneity leads to conflict and chaos	3:1	Spontaneity brings people with the same interests together	0:4
Leadership and its origin, eligibility, and function: who should be leaders, why a group needs a leader, and what a leader should do.	Leaders come from the outside	5:1	Leaders emerge from within	0:4
	Leaders are arbitrators; they set rules	5:2	Leaders are initiators; they set examples	0:3
Natural changes over time: expected changes in a system over time if there is no outside intervention.	A system will deteriorate in the long term	5:2	A system will improve itself in the long term	0:6
Responsibilities and functions of institutional structures: roles of institutional structures such as law and policy.	Institutional structures should actively intervene to restore social order	6:3	Institutional structures should merely establish a common platform	2:4

These themes were not mutually exclusive; they overlapped and connected in a coherent manner. This interconnectedness revealed two general positions—hands-off and hands-on mindsets. The hands-off mindset assumes that individuals are spontaneously bound to each other. This is a precondition for the assumption that members tend to follow a capable leader from among themselves, which itself is a precondition for the optimistic belief that social members will gradually improve society by themselves. These assumptions are prerequisites for more relaxed social control. The hands-on mindset assumes that conflicts of interest spontaneously drive individuals apart. This assumption presupposes that external agencies deliver leadership and arbitration, without which a total collapse within the system is foreseeable in the long term. Because of these assumptions, active social control is preferable to the alternatives.

6.4. Thematic Consistency between Individuals and Differences between Groups

The questions remaining were (a) whether the participants spoke consistently within a single mindset and (2) whether there was a difference in the themes and the mindsets between the ENT and SEO groups. Table 2 shows the consistency of mindset within groups and the differences between the groups. The participants from the ENT group were almost exclusively framed within the hands-on mindset. The participants from the SEO group

were predominantly framed within the hands-off mindset, although some of them also considered positions from the hands-on mindset.

7. Discussion

We began this research by asking if science learners may romantically transfer thermodynamic theories to give endorsement and construct narratives in ideas about social control. In summary, the quantitative and interview findings, taken together, tell a rich and complex story of students' romantic transfer:

1. The participants who learned different science concepts could transfer them to different domains of social ideologies. In some cases, those who learned about entropy were more likely to prefer tightened external control, whether in the field of politics or marketing, whereas those who learned self-organisation theory were more likely to prefer relaxed external control and more individual freedom. However, the transfer did not occur in all cases.
2. There were multiple possible domains to which the participants transferred. However, the participants did not transfer to all of the domains under investigation.
3. Participants from different groups took different positions in their social discourse but shared similar positions within their groups, and their positions were largely consistent with the implications of the science concept that they had learned.
4. The participants did not directly borrow the lexicon from the science domain to reason in the social domain; instead, they organised their language to rephrase the scientific theory and explain their personal social beliefs.

The interaction effect between treatment and budget (from the pre-test) on the amount of donation was an interesting finding that this study did not directly explain. Two speculative explanations might be considered. First, the participants with strict budgets may have thought more carefully about the size of their donation and more actively sought a good reason to donate than the participants without strict budgets. They might have stronger empathy about the meaning and usefulness of this small amount of money, and as a result, they were more responsive to the intervention [42]. In comparison, the students with abundant charity budgets donated close to the maximum amount, regardless of their treatment conditions. A second speculative explanation was simply the ceiling effect. The question in the survey set the maximum to 50 RMB. Thus, even if the participants at the budget's higher end had wanted to donate more to the club, they would not have been allowed to do so. In this case, there could also have been a treatment effect for the participants with a higher budget (two parallel lines instead of the convergent lines) had there been no donation cap. Although the second explanation was possible, the data did not fully support it because there were very few participants who claimed to be willing to donate the full amount to the club, meaning that the ceiling was rarely reached.

This study adds to the literature that science learners may transfer scientific concepts to personal, civic ideas (e.g., [23,27,41,43]) and recognize principles that arise in different domains, such as feedback loops, and can explain phenomena in both physics, chemistry, economy, and society [44–47]. The interview data gave us a glimpse into the mental models on which the participants relied when they discussed social organizations. We assumed that the two groups of students started off with similar science backgrounds and civic preferences before the experiment because of random assignments (supported by a balance check between the two groups). Participants who learned the entropy concept in the context of thermodynamic theory might metaphorize human society as an entropy system that would become chaotic spontaneously without higher ordered power and control. According to the interview data, this metaphor had a structured mapping; for example, the randomness that cripples the thermodynamic system might correspond to the rule-breakers in the society, and the order of particles might correspond to the togetherness in human collective intentions. Participants who learned the self-organization concepts, also in the context of thermodynamic theory, metaphorized human society as a self-organized system that would spontaneously form order from within needless of strong external control.

The self-reinforcing feedback loop in the thermodynamic system might correspond to the initiation of local leadership that assimilate others in the society. In comparison, the two groups would generate very different implications of the learned science concept to social control—one (the entropy group) favored strong government intervention because society will crumble overtime, and the other one (the self-organization group) favored self-governance because the social order will self-organize (with proper local leadership and reinforcement). This was evidenced in participants' endorsement of behaviors in case studies and participants' willingness to pay (donate), with the caveats that some effects were small or non-significant.

The most striking finding was that none of the students directly cited thermodynamic theories. None of the students claimed that they supported or were opposed to hierarchical regulation because of entropy or self-organisation theory. This suggested that the participants were not aware that the interview was related to their science lectures (the interviewers and lecturers were different people from the research team), and they were not trying to give answers that would be agreeable to the research team. This result might appear to disprove the hypothesis that the students actively draw on scientific theories to support their social beliefs. However, given the systematic difference in the participants' narratives between groups, we can reasonably argue that the participants generated (or selected) and relied upon personal wisdom that was consistent with the scientific treatment they received, even though they did not give direct credit to the science lecture but assumed the wisdom to be their own. The science model might have encouraged the participants to shape their mental models for social organisation purposes, but for various reasons, they avoided using the physics terminology directly. One possible explanation was that the participants were not fully comfortable with using the new academic terminology, or perhaps they did not remember the exact (and low-frequency) terminology, although they understood and had been affected by the essence of the terminology. The literature on the transfer of learning showed that explicit and critical evaluation of the patterns, similarities, metaphors, and analogies might catalyze learning transfer [48–51]. Yet, our study intentionally avoided making this explicit association in the instruction because we wanted to investigate to what extent the romantic transfer was spontaneous. This lack of explicit association might explain why we detected some of the treatment effects as non-significant and why students did not explicitly use the physics terminologies. This may be reflected in the literature that showed that the transfer of learning is both ubiquitous and rare [24,29]—ubiquitous in that learners were influenced implicitly, and rare because learners have not formulated their ideas in explicit analogies.

7.1. Limitations

It is important to discuss the fact that we did not observe transfer in every case. Among the survey items, we observed that four out of nine items showed an effect on transfer. However, if we adopted a conservative threshold, we only observed one item to be significant. We used different domains and scenarios to 'trap' transfer because we knew from the literature that transfer might be rare and that it might occur in unexpected ways. Our findings concurred with the literature in this respect. One explanation might be that the participants had not developed a deep impression or digested the messages of the theories. As mentioned above, the interview data showed that the participants did not directly quote the theories discussed in the lectures, indicating that they had not fully incorporated those theories into their lexicon or worldview. Most of the examples of romantic transfers mentioned in the literature originated from scientific theories with which the learners or scientists were very familiar (e.g., theories that were repeatedly discussed in classes, tested in exams, or studied in research). A 40 min math-free conceptual introduction might not have been enough to yield an effect on a 4-point Likert scale. Students who did not have strong opinions would rate the two opposing opinions equivalently. However, when we pushed the interviewees to choose their preferences and gave them enough time to reason in the interview sessions, we observed that they were implicitly influenced by

the treatments. It would be intriguing to ask about the extent to which the structure or the context of the different case studies facilitated or hindered transfer. Was it possible that most of the students already had personal experience of self-directed learning and that, as a result, their opinions about assigning head teachers to MOOCs were less likely to be influenced by a brief intervention, compared with issues that were more abstract or less familiar to them? Unfortunately, our experiment was not designed to discern this effect.

7.2. Implications

On the bright side, romantic transfer has potential utility in social and civic education because scientific theories provide a reasonably continuous supply of new mental models for transfer. On the dark side, the teaching of science could also be used abusively for social programming.

Romantic transfer from scientific models often appears more convincing and powerful than textbook knowledge because it involves intuitive metaphors generated by the learners themselves. Polkinghorne [52] noted that 'when scientists use apparently metaphorical language—as in talk of "black holes" or the "genetic code"—they are using these terms as picturesque shorthand for ideas they can more readily and more adequately convey in precise scientific language, and they are not using them as imaginative resources for the generation of ideas in a truly metaphorical way' (p. 20). His remark is an important reminder that scientists, although making aesthetic choices in their use of such 'nicknames', are not overly romantic in their understanding of the essence of these concepts in their own minds. However, Polkinghorne's remark does not 'do justice to the way metaphors determine what can and cannot be thought' [53] or who can and cannot combine romance with science.

Donovan [40] argued that the risk of problematic transfer could be reduced by teaching students about the complexity of the concept domain and then teaching them to understand research methods and limitations. In addition, we suggest that once a student invests his/her intelligence and imagination in romantic transfer, educators are afforded an exceptional opportunity to engage him/her in explicit debate and discussion. This opportunity allows educators to introduce not only scientific methods that examine nature but also additional tools to examine social hypotheses. Based on our findings, it is evident that students can transfer to many different (and unexpected) domains. Thus, pedagogically, it is most efficient to ask students to brainstorm and elaborate upon their free transfers rather than make presumptions about the direction of their transfers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci13060599/s1, Supplementary File S1. Specific wording for the case studies. Supplementary File S2. Themes, positions, and examples of participants' narratives.

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